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TITLE: LINE DRAWING FOR A VOLUMETRIC DISPLAY
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LINE DRAWING FOR A VOLUMETRIC DISPLAY

This invention relates to computer graphics, and in particular, to the rendering of a straight line in a volumetric display in which the voxels are arranged on a cylindrical coordinate grid.

CLAIM OF PRIORITY

Under 35 USC §119(e)(1), this application claims the benefit of the priority date of U.S. Provisional Patent Application Serial No. 60/230,972, filed on September 7, 2000, the contents of which are herein incorporated by reference.

BACKGROUND

Many computer-implemented displays consist of two-dimensional arrays of individual picture elements, or pixels. To form an image, a rasterizer selectively illuminates these pixels. Because the individual pixels are so small, the display appears, to a human viewer, to be a continuous rendering of an image. This illusion is particularly effective for complex images of continuous tones such as photographs.

For simple geometric shapes, however, the pixelated nature of the display can become apparent to the human viewer. For example, if the rasterizer is instructed to draw a straight line, there is no guarantee that the points on that desired line will coincide with the pixels that are available for rendering the line. As a result, the desired line is often rendered as a rasterized line of pixels that are close to, but not necessarily coincident with, the desired line. This results in rasterized lines that have a jagged or echeloned appearance.

In the course of rendering an image, a large number of straight lines and line segments are often drawn. As a result, given a desired line, the rasterizer must frequently select those pixels that will minimize the jagged appearance of the resulting rasterized line. A straightforward mathematical approach is to use the equation of the desired line and the coordinates of the available pixels to minimize a least-square error across all points on the line. While such an approach has the advantage of globally optimizing the selection of pixels on the rasterized line, the large number of floating-point operations required causes this approach to be prohibitively time-consuming.

To meet constraints on speed, rasterizers typically implement rasterization methods that avoid time-consuming floating-point operations. Among the methods that meet the foregoing constraints is that taught in *Bresenham, J.E.*, Algorithm for Computer Control of a Digital Plotter, IBM System Journal, Vol. 4, pp.25-30, 1965, the contents of which are
 5 herein incorporated by reference. Using only integer operations, the Bresenham algorithm reduces the choice of what pixel to select to an examination of the sign of a discriminant.

Even faster rasterization methods exist that select not one but multiple points on the rasterized line based on the outcome of a single decision. There also exist a variety of rasterization methods aimed at rendering conic sections and quadric sections on a pixelated
 10 display.

However, the foregoing rasterization methods all rely on the assumption that the array of pixels is arranged in a uniform rectangular grid that can readily be modeled by a Cartesian coordinate system. This was a reasonable assumption given the prevalence of two-dimensional displays such as computer monitors and printers at the time these
 15 algorithms were developed.

Since then, however, volumetric, or three-dimensional displays have been developed. Such displays permit the generation, absorption, or scattering of visible radiation from a set of localized and specified regions within a volume. Examples of such systems are taught in *Hirsch* U.S. Patent No. 2,967,905, *Ketchpel* U.S. Patent No.
 20 3,140,415, *Tsao* U.S. Patent No. 5,754,147, and on pages 66-67 of *Aviation Week*, October 31, 1960.

SUMMARY

The method of the invention provides for rapid rendering of a desired line in a volumetric display having a rotatable screen. The method includes stepping the rotatable screen through a
 25 sequence of angular positions. At each angular position, a rasterized approximation of a line segment containing an intersection of the desired line and the rotatable screen is rendered on the screen.

In one aspect of the invention, the screen is positioned at a first angular position in which the screen is coplanar with an entry plane. A first and second voxel are then selected on the basis

of the geometric relationship between the desired line and the entry plane. In particular, the first voxel corresponds to an intersection of the desired line with the entry plane; and the second voxel corresponds to a projection, onto the entry plane, of an intersection of the desired line with an exit plane. A connecting segment that connects the first and second voxels is then rasterized by
5 rendering selected voxels on the two-dimensional screen.

The rasterization of the connecting segment can be carried out by an algorithm such as the Bresenham algorithm. However, any two-dimensional rasterization algorithm can be used to rasterize the connecting segment.

In one aspect of the invention, the first voxel is selected by obtaining constants that define
10 the desired line in cartesian coordinates and obtaining an angle descriptive of the angular position of the entry plane. On the basis of the constants and the angle, a trigonometric transformation determines cylindrical coordinates of the intersection of the desired line with the entry plane.

In some cases, the optical layout of a volumetric display introduces distortions that are corrected by additional, optional steps in the method. For example, the distortion introduced by
15 rotation of the imaging screen can be corrected by generating rotated coordinates corresponding to the first voxel, the rotated coordinates corresponding to rotation about a selected angle. Similarly, correction of distortion resulting from keystoning can be achieved by generating projected coordinates corresponding to the first voxel, the projected coordinates being obtained by correction for keystone distortion.

20 These and other features and advantages of the invention will be apparent from the following detailed description, and the figures, in which:

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is a volumetric display;

FIG. 2 is a planar view of the display volume;

25 FIGS. 3 and 4 show one method of rasterizing a line in a three-dimensional space; and

FIGS. 5 and 6 show a second method of rasterizing a line in a three-dimensional space.

DETAILED DESCRIPTION

A volumetric display **10** for practice of the invention, shown in FIG. 1, includes a base section **11** and a rotating section **12**. A motor controller **13** causes a motor (not shown) to spin the rotating section **12** rapidly about an axis **16** coupled to the base section **11**.

Within the base section **11**, a light source **18**, under the control of a rasterizer **20**, generates a spatially varying pattern of light for illuminating selected pixels **22** on the imaging screen **14** at successive instants. A typical light source **18** includes a micro-mechanical array of individually addressable mirrors whose orientations are under the control of the rasterizer **20**. This light is passed into the rotating section **12** through a stationary optical subsystem **15** in optical communication with a rotating optical subsystem **17** coupled to the rotating section **12** and coaxial with the axis **16**.

Light from the rotating optical subsystem **17** is projected onto a central mirror **19** disposed above the rotating optical subsystem **17** and angled to direct light toward a first relay mirror **21** disposed at the periphery of the base section **11**. The first relay mirror **21** is angled to reflect light to a second relay mirror **23** at the periphery of the base section **11**. The second relay mirror **23** is angled to direct light from the first relay mirror **21** toward the imaging screen **14**.

These pixels to be illuminated on the imaging screen **14**, and the instants at which they are to be illuminated, are determined by the rasterizer **20** on the basis of data indicative of the angular position of the imaging screen **14** (as supplied by the motor controller **13**) and data descriptive of a three-dimensional image (as stored in a data source **25**).

As the rotating section **12** spins around the axis **16**, the imaging screen **14** sweeps out a display volume **27** within the rotating section **12**. If the rotating section **12** were to spin rapidly enough, and if the successive instants of illumination were to be separated by sufficiently brief time intervals, a continuous curve would appear to hang in mid-air within the display volume **27**.

FIG. 2 illustrates the projection onto a plane perpendicular to the axis **16** of a desired line **24** to be approximated by the rasterizer **20**. In FIG. 2, the imaging screen **14** is shown in six successive instants as it rotates around the axis **16**, now perpendicular to the page. At each of the six instants, the light source **18**, under the control of the rasterizer **20**, illuminates a pixel **22** on the imaging screen **14**. As shown in FIG. 2, by aiming the light source **18** at the correct pixel and

firing the light source **18** at the right times, it is possible to trace out a rasterized line that approximates the desired line **24**. It is the function of the rasterizer **20** to correctly aim and fire the light source **18** so as to trace out this desired line **24**.

To aim the light source **18**, the rasterizer **20** needs a way to identify points in space. In other words, the rasterizer **20** needs a coordinate system. One possible coordinate system is a Cartesian coordinate system.

Using a Cartesian coordinate system, the rasterizer **20** would draw the desired line in FIG. 2 by specifying, for example, that at time t_1 , the light-source **18** should aim 30 units north, at time t_2 , the light-source **18** should aim 29 units north, 1 unit east and 1 unit in elevation, at time t_3 , the light-source **5** should aim 28 units north, 2 units east and 2 units in elevation, and so on. To ensure that the imaging screen **14** is at the appropriate location, the rasterizer **20** also has to specify the values of the times t_1 , t_2 and t_3 based on how fast the imaging screen **14** spins. Although the spinning of the imaging screen **14** can be resolved into a north-south component and an east-west component, this is a computationally taxing exercise that can easily be avoided by using a cylindrical coordinate system.

As an alternative, the rasterizer **20** could draw the line in FIG. 2 in cylindrical coordinates by specifying, for example, that at time t_1 , the light source **18** should aim 30 units away from the axis **16** at a 90 degree angle, at time t_2 , the light source **18** should aim 29.02 units from the axis **16** at an angle of 88.03 degrees and point up by 1 unit of elevation, and at time t_3 , the light source **18** should aim at 28.07 units from the axis **16** at an angle of 85.91 degrees and point up by 2 units of elevation. This would, of course, draw the same line that was drawn using Cartesian coordinates. The advantage of using cylindrical coordinates becomes apparent when it comes time to specify when to fire the light source **18**. Because the imaging screen **14** is spinning, it is far more natural to represent its motion in terms of degrees per second than it is to resolve its motion into a north-south component and an east-west component. For this reason, calculations involving motion of the imaging screen **14** in a volumetric display **10** are best performed in terms of a cylindrical coordinate system.

The process of rendering a line in a cylindrical coordinate system is fundamentally different from that of rendering a line in a Cartesian coordinate system. In a Cartesian coordinate

system, a line has a constant slope. A unit change in one direction always results in the same change in the remaining two directions, regardless of where that change occurs. This is not the case in a cylindrical coordinate system.

In a cylindrical coordinate system, the slope of a line can vary dramatically with position along the line. In contrast to a Cartesian coordinate system, in which the slope of a line is constant at all points on the line, the slope of a line in a cylindrical coordinate system can vary significantly along the line. This is because the coordinate grid in a cylindrical coordinate system is not a spatially uniform grid, as is the coordinate grid in a Cartesian coordinate system.

For those portions of the line that are closest to the axis of the cylindrical coordinate system, the change in distance of the line from the origin changes very slowly with angle. For those portions of the line that are far from the axis of the cylindrical coordinate system, even a small change in angle results in a huge change in radial distance from the axis.

In the volumetric display **10** of FIG. 1, the rasterizer **20** causes a sequence of images to be projected onto the imaging screen **14**. The particular image displayed on the imaging screen **14** depends on the angular position of the imaging screen **14** as it rotates about its axis **16**. The image does not, however, vary continuously with angular position of the screen **14**. Instead, the displayed image remains constant for a particular range of angular positions, changing only when the angular position of the screen **14** crosses one of a plurality of threshold angles. These threshold angles are typically equally spaced and very close together. In the illustrated embodiment, the angular separation between threshold angles is between 30 minutes and 1 degree of arc.

The display volume of the volumetric display **10** can thus be viewed as a cylindrical volume of intersecting planes, all of which intersect at the axis **16** about which the imaging screen **14** rotates. In the cross-sectional view of FIG. 2, each pair of intersecting planes defines a wedge-shaped slice **28**. The two planes that bound a slice are referred to as the “entry plane **30**” and the “exit plane **32**” for that slice **28**. As the screen **14** rotates about its axis **16**, it becomes momentarily coplanar with the entry plane **30** for a particular slice **28**, it then traverses that slice **28**, and becomes coplanar with the exit plane **32** for that slice **28**. As is apparent from FIG. 2, the exit plane **32** for a slice **28** is thus coplanar with the entry plane for a following slice **33**.

When the imaging screen **14** is coplanar with any entry plane **30**, the image displayed on the screen **14** is permitted to change. As the imaging screen **14** traverses a slice **28**, the image displayed on the screen **14** remains constant. Data generally available to the rasterizer **20** for drawing the desired line **24** includes data from which the Cartesian coordinates of at least two points (x_0, y_0, z_0) and (x_1, y_1, z_1) can be obtained. From these two points, the following constants descriptive of the desired line **24** are calculated:

$$\theta_t = \arctan\left(\frac{y_1 - y_0}{x_1 - x_0}\right)$$

$$d = \frac{|x_0 \cdot y_1 - x_1 \cdot y_0|}{\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2}}$$

$$\gamma = \frac{d \cdot (z_1 - z_0)}{\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2}}$$

$$h_t = z_0 - \frac{(x_0 \cdot (x_1 - x_0) - y_0 \cdot (y_1 - y_0)) \cdot (z_1 - z_0)}{(x_1 - x_0)^2 + (y_1 - y_0)^2}$$

These constants need only be computed once for each desired line **24**. In the illustrated embodiment, d is a 16-bit fixed point signed number, h_t is a 40 bit fixed point number, and γ is a 16-bit fixed point signed number.

To improve performance, values of θ_t are obtained from a look-up table. The look-up table is kept as small as possible by selecting a resolution of θ_t that is coarse, but not so coarse as to significantly degrade the accuracy of the rasterization. In particular, if the resolution of θ_t is coarser than the θ resolution of the display space, values of θ corresponding to different planes can be mapped to the same r and h values. This causes an undesirable loss of resolution in the θ direction.

In the illustrated embodiment, the number of entries in the look-up table is double the θ resolution of the display space. This ratio provides sufficient accuracy to eliminate most visual artifacts and to avoid degrading the minimum resolution of the display **10**.

Given these constants, the rasterizer **20** then obtains the cylindrical coordinates of the intersection of the desired line **24** with each of the intersecting planes, as shown in FIG. 2. These intersection points are given by

$$r(\theta) = d \cdot \sec(\theta - \theta_i)$$

$$h(\theta) = h_i + \gamma \cdot \tan(\theta - \theta_i)$$

where θ is the angle associated with a particular intersecting plane.

One approach, shown in FIG. 3, to rendering the desired line **24** is to select that voxel **26** on the entry plane **30** that is closest to the intersection of the desired line **24** with that plane. The rasterizer **20** then illuminates that selected voxel **26** throughout an interval beginning with the instant the screen **14** becomes coplanar with that entry plane **30** and ending just before the screen **14** rotates into the exit plane **32** for that slice **28**. This process, when repeated for successive slices, results in a rasterized line that approximates the desired line **24**.

A difficulty with the foregoing method is that unless the θ resolution is prohibitively high, the resulting rasterized line appears as a discontinuous sequence of circular arcs **34**, as shown in FIG. 4. Each arc **34** has an arc length proportional to the angle swept out by the screen **14** as it traverses a particular slice **28**.

To remedy this, the rasterizer **20** determines the intersection points of the desired line **24** with the entry plane **30** and the exit plane **32** (hereafter referred to as the “entry point **36**” and “exit point **38**” respectively) as described above. When the screen **14** becomes coplanar with the entry plane **30**, the rasterizer **20** renders a voxel corresponding to the entry point **36**. In addition, the rasterizer **20** determines the projection of the exit point **38** (hereafter referred to as the “projected exit point **40**”) onto the entry plane **30**, as shown in FIG. 5. This defines a connecting segment **42** on the screen **14** that connects the entry point **36** with the projected exit point **40**. The rasterizer **20** then renders voxels on the screen **14** that rasterize this connecting segment **42**. This rasterization can be carried out using conventional two-dimensional rasterization algorithms, such as the Bresenham algorithm.

The rasterization method of the invention thus achieves three-dimensional rasterization in a cylindrical coordinate system by performing a sequence of two-dimensional rasterizations on the imaging screen **14** as that imaging screen **14** sweeps out a cylinder in a three-dimensional volume.

As the screen **14** traverses the slice **28**, the connecting segment **42** rendered on that screen **14** traces out a planar strip **44** having a width and orientation corresponding to that of the connecting segment **42**, as shown in FIG. 6. Because the threshold angles are close together, only a few pixels separate the entry point **36** and the projected exit point **40** on a plane. The connecting segment **42** is thus a short line segment. As a result, the planar strip **44** traced by the screen **14** is a only a few voxels wide.

As the screen **14** approaches the exit plane **32**, the projected exit point **40** on the connecting segment **42** approaches the exit point **38**. This exit point **38** is also the entry point for the following slice **33**. As a result, the planar strips traced out by the connecting segments appear to merge smoothly into each other, resulting in the display of a smooth line in three dimensions.

Although the rasterization method has been discussed in the context of a cylindrical coordinate system, it is also applicable to coordinate systems that can be derived from a cylindrical coordinate system by rotations and projections. Certain volumetric display devices, such as the one illustrated in FIG. 1, introduce particular image distortions which require correction.

A first type of image distortion is made apparent when the light source **18** projects a static image on the spinning imaging screen **14**. When it does so, the static image will appear to rotate about the center of the imaging screen **14**. This type of distortion is referred to as “rotational distortion.”

A second type of distortion is made apparent when the light source **18** projects an image of a rectangle on the imaging screen **14**. When it does so, the rectangle appears distorted into a keystone. This type of distortion, referred to as “keystone distortion,” occurs because the optical path from the bottom of the image on the screen **14** to the focus of the light source **18** is shorter than the optical path from the top of the image to the focus.

Consequently, the top portion of the image projected by the light source **18** undergoes greater magnification than the bottom portion of the image.

For display devices that require correction for keystone and rotation distortions, it is desirable to execute an additional step between the calculation of cylindrical coordinates of the entry point **36** and the projected exit point **40** and the rasterization of the connecting segment **42**. The cylindrical coordinates of the entry point **36** and the projected exit point **40** are calculated to have angle, radius and height of (θ_1, r_1, h_1) and (θ_2, r_2, h_2) , respectively. The keystone distortion is corrected by a projection operation on the vectors (r_1, h_2) and (r_2, h_2) to give vectors (r'_1, h'_1) and (r'_2, h'_2) . The rotation of the image of the light source **18** on the screen **14** is corrected by an opposite rotation about the center of the screen **14**. The vector (r'_1, h'_1) is rotated by an angle $-\theta_1$, resulting in a vector (x_1, y_1) . The vector (r'_2, h'_2) is rotated by an angle $-\theta_2$, resulting in a vector (x_2, y_2) . The vector (x_1, y_1) specifies the point on the light source **18** which must be illuminated to render the entry point **36** on the imaging screen **14** at the instant when the rotating section **12** is rotated to an angle θ_1 . The vector (x_2, y_2) likewise specifies the point on the light source which must be illuminated to render the projected exit point **40** on the imaging screen **14** at the instant when the rotating section **12** is rotated to an angle θ_2 . The connecting line segment **42** is drawn on the light source **18** using the coordinates (x_1, y_1) and (x_2, y_2) as endpoints. Display designs resulting in optical paths that differ from that shown in FIG. 1 may require one or the other, or none of the foregoing distortion corrections.

The source code in the attached appendix teaches a particular implementation of the foregoing rasterization method. In the source code, the variable "x" is a vector and variables beginning with "q" are angles. The function "bres2d(x, x_, q)" implements a conventional Bresenham algorithm for rasterizing a line extending from x to x_ within a plane associated with slice q; the function "ang_add(q, q_)" adds angles q and q_; the operation "x->(r, h)" decomposes a vector in the r-h plane into its r component and its h component; and the operation "x=(r, h)" forms a vector in the r-h plane having components r and h.

The following source code makes reference to a projected coordinate system. The projected coordinate system is related to the cylindrical coordinate system described above through tumbling and keystoneing operations. These operations are shown as italicized text in the following source code.

5 Having described the invention, and a preferred embodiment thereof, what is claimed as new and secured by letters patent is:

APPENDIX

```

line_polar_pos(q, d,gamma,phi,gs,h_t )
{
    th = ang_add(q,-phi);
5
    if( th >= TRIG_PI )
        th -= TRIG_PI;

    if( th<TRIG_PI_2 )
        sec_tan = sec_tan_table[th];
    else
        sec_tan = sec_tan_table[TRIG_PI-1-th];

    sec_tan -> (sec,tan);
15
    /* tmp = gamma*tan(theta) */
    tmp = gamma*tan;
    if( th>=TRIG_PI_2 )
        tmp=-tmp;

    /* r = abs(d*sec(theta)) */
    /* h = ((gamma*tan(theta))>>gs) + h_t */
    r = (d*sec)>>(1+_he_tan_shift);
    h = (((gamma*tan)>>gs) + h_t)<<16;
25
    return (r,h);
}

/* Calculate position along line in projected coordinate space*/
30 line_pos( q, d,gamma,phi,gs,h_t)
{
    x = line_polar_pos(q,d,gamma,phi,gs,h_t);
    cyln2projected(q,x);
    return (x);
35
}

/* Advance slice and carry state */
next_slice( *q, *x, x_ )
40
{
    /* increment the slice number */
    *q = ang_slice_inc(*q);

    /* leading edge of next slice is this slice's trailing edge */
    if( slice_number(*q) == 0 )
45
        *x = (x_^0xffff0000)+0x00010000; /* Compensate for Pi jump by negating h */
    else
        *x = x_;
}

50
line_sub( q, q_end, x0, x1, d,gamma,phi,gs,h_t )
{
    x0 = cyln2projected(q, x0);
    x1 = cyln2projected(q_end,x1);
55
    /* First vertex of line */
    if( q!=q_end )
        line_next_slice(&q,&x,x0);
    else
        x = x0;
60
    /* Draw middle slices of line */
    while(q!=q_end) {
        x_ = re_line_pos(q, d,gamma,phi,gs,h_t);
        bres2d(q,x,x_);
        line_next_slice(&q,&x,x_);
    }

    /* Draw final slice of line */
70
    x_ = x1;
    bres2d (q,x,x_);
}

/* Draw a line in cylindrical (projected) coordinates from (q0,x0) to

```

```

(q1,x1) using cylindrical line constants d,gamma,phi,gs,h_t */
line(q0,x0, q1,x1, d,gamma,phi,gs,h_t)
{
  /* Front scan */
  q = q0;
  q_end = q1;
  line_sub(q,q_end,x0,x1, d,gamma,phi,gs,h_t);

  /* Back scan */
  q = ang_fixup(q +TRIG_PI);
  q_end = ang_fixup(q_end+TRIG_PI);
  line_sub(q,q_end,x0,x1, d,gamma,phi,gs,h_t);
}

```

15 Additional subroutines for use with "projected" coordinate system

```

line_dekeystone(x)
{
  x -> (_xx,_yy); /* decode x vector into (x,y) components */
  int i = ((_yy + (FB_YLINES<<5)) >> 6) << 1; /* index in key_table */

  /* clip i to table size */
  if(i>1534)
    i=1534;
  else if(i<0)
    i=0;

  xx = ((_xx*key_table[i]) >> key_shift) + cx_1key;
  yy = ((_yy*key_table[i+1]) >> key_shift) + cy_1key;

  return (xx,yy);
}

```

```

line_detumble(q, x)
{
  x -> (r,h); /* extract r and h parts of x vector */

  /* 2d rotation: */
  /* x = r*cos(th) + h*sin(th) */
  /* y = h*cos(th) - r*sin(th) */

  if(q>=TRIG_PI) {
    r = -r; /* Pi..2Pi maps back to 0..Pi with r negated */
    q -= TRIG_PI;
  }

  /* rotate by -q */
  x1 = r*cos(q);
  x2 = -h*sin(q);
  y1 = h*cos(q);
  y2 = r*sin(q);

  xx = (x1+x2)>>15; /* sin/cos tables have 15 fractional bits */
  yy = (y1+y2)>>15;

  return (xx,yy);
}

```

```

cyl2projected(q,x)
{
  x_ =line_dekeystone(x);
  x__=line_detumble(q,x_);
  return x__;
}

```